

Dynamic Fracture-Resistance Testing and Methods for Structural Analysis

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20. Abstract (Continued)

design tool, empirical correlations between practical dynamic test results and the basic parameters are needed. The attributes and limitations of the Charpy, Drop Weight-Nil Ductility Transition Temperature, Drop Weight Tear, and Dynamic Tear tests are discussed with respect to providing information useful in structural integrity analyses.

CONTENTS

INTRODUCTION	1
TESTING VARIABLES AND ANALYSIS OF TEST RESULTS.....	1
Effects of Strain Rate	1
Effects of Constraint	2
Effects of Stable Crack Extension	3
CHARPY-V NOTCH TEST (ASTM E23)	4
DROP-WEIGHT, NIL-DUCTILITY TRANSITION (NDT) TEMPERATURE TEST (ASTM E208)	6
Explosion Bulge Test	6
Critical Temperature Concept	7
DROP-WEIGHT TEAR TEST (ASTM E436)	10
DYNAMIC TEAR TEST (MIL-STD(SHIPS) 1601)	11
Specimen Design	12
Analysis of DT Energy	13
SUMMARY	19
ACKNOWLEDGMENTS	20
REFERENCES	21
GLOSSARY	23

DYNAMIC FRACTURE RESISTANCE TESTING AND METHODS FOR STRUCTURAL ANALYSIS

INTRODUCTION

The recently developed linear elastic fracture mechanics (LEFM) was a milestone in engineering technology. It provided a basic relationship between the material and the structural aspects of fracture which formed the basis for an analytical approach to structural integrity. Traditionally, the results of impact tests were used as arbitrary criteria for the acceptance of materials in various design codes, rules, and guides. Unfortunately, the traditional design procedures using ratios of tensile strength and factors of safety did not always preclude fracture; and there was no flexibility in the design procedures to scale up the resistance to fracture and improve reliability. This dilemma was changed substantially with the analytical capability of LEFM and the standardization in 1972 of the Plane-Strain Fracture Toughness Test as ASTM E399.

The Plane-Strain Fracture Toughness Test has two severe limitations for general engineering use. It is too expensive to conduct on a routine basis, and it applies only to the static properties of brittle materials. Within limited bounds, however, a LEFM analysis can be extrapolated into the elastic-plastic regime where most structural metals operate. Allowances can be made also for dynamic loading; with extrapolations, boundary conditions can be defined for a stepwise definition of structural performance and a better understanding of the mechanics of the conventional impact tests. This understanding has led to a recognition of the basic limitations of the two most widely used conventional impact tests, the Charpy V-notch (C_v) test, and the Drop-Weight, Nil-Ductility-Transition (DWT-NDT) test [1,2,3]. To circumvent these limitations, a new test with a wide-range measuring capability was developed [4].

The new test method is called the Dynamic Tear (DT) test. It was designed as a practical test for general use, keeping the simplicity of a three-point bend specimen and an energy criterion for fracture resistance. Although the primary purpose of the DT test is to provide information on materials used in structures requiring some ductility even though flaws may be present, empirical correlations have been made between DT energy (DTE) and K_{Ic} values for various high-strength alloy systems [4].

TESTING VARIABLES AND ANALYSIS OF TEST RESULTS

Effects of Strain Rate

The applicability of fracture resistance data that is generated by the high strain rates associated with impact tests has been questioned for statically loaded structures. Stress-intensity rates from 3×10^4 to 1×10^6 $\text{MN} \cdot \text{m}^{3/2}/\text{s}$ (3×10^4 to 1×10^6 $\text{ksi} \sqrt{\text{in.}}/\text{s}$), causing fracture to occur in 1 to 0.1 ms, are common in specimens under conventional impact loading rates. This relatively high strain rate may be several orders of magnitude higher than that

encountered in elements of bridges, ships, or pressure vessels. Service experience has shown, however, that the catastrophic fractures of large welded structures are related to the dynamic, high-strain-rate properties of the materials even though the loading rates on a structure may be intermediate. A flaw or crack may be dormant for years, with unstable crack extension controlled by the static fracture-resistance properties, but when the conditions at the crack tip cause a few grains to fracture by cleavage, the local mechanics change drastically. The local strain rate associated with the "pop-in" is similar to that in an impact test; continued extension of the crack is then dependent upon the dynamic properties of the material even though the structure is under a static load. Therefore, dynamic tests are not only conducted for economic reasons, but they are also needed to provide information related to potential structural performance under emergency conditions, such as a small pop-in crack or a plastic overload.

The high loading rates associated with impact tests impose a complex mechanical condition in the specimen. Recent analyses of the mechanical conditions in impact tests have shown that for loading rates that cause fractures to occur in less than 1 ms, the striker force may not be in phase with the bending moment. This complicates the generation of dynamic K_{Ic} or J_{Ic} values, frequently referred to as K_{Id} or J_{Id} values [5,6]. To obtain K_{Id} values under impact conditions, the impact velocity is frequently decreased to the point where a static analysis can be employed, or the specimen is instrumented to obtain an accurate measure of the strain level associated with fracture [6,7].

Caution must be exercised when any generalities are proposed for the effects of intermediate loading rates that cause fracture to occur in less than 1 ms. A recent study involving a variety of bridge steels showed that the shift in the temperature of the transition region due to strain rate is complex and is not a predictable characteristic for a broad range of steels [8,].

Effects of Constraint

Constraint has a very significant effect on the initiation of cleavage fracture in ferritic steels; therefore, it has an important influence on the temperature at which the ductile-to-brittle transition in fracture resistance occurs. Constraint is related to any dimensional parameter that tends to restrict plastic flow at the notch tip. This includes the depth of the notch, the sharpness of the tip of the notch, and the thickness of the section. Because of the unpredictable effect of side grooves on fracture resistance in the elastic-plastic regime, side grooves are not generally used on impact specimens.

Constraint is designed in a specimen by the use of a notch with a sharp tip and a notch depth sufficient to prevent the plastic zone from extending to the top surface of the specimen. The level of constraint developed by a specimen can be defined as the capability of the specimen to cause fracture under the conditions defined as "plane-strain" in ASTM E399. For plane-strain fracture to occur, the thickness of the specimen must comply with the following conditions:

$$B \geq 2.5(K_{Ic}/\sigma_{ys})^2 \quad (1)$$

where

B = thickness, m (in.)

K_{Ic} = critical stress-intensity factor $\text{MPa}\sqrt{\text{m}}$ ($\text{ksi}\sqrt{\text{in.}}$)

σ_{ys} = yield strength, MPa (ksi).

The relationship in Eq. (1) is useful for evaluating the effects of section size on the transitions in the fracture resistance of structural metals. These sharp changes in fracture resistance occur with relatively small changes in yield strength or temperature. The "strength transition" is an important characteristic in the fracture properties of high-strength metals; the "temperature transition" is an important characteristic in the fracture properties of the more widely used ferritic irons and steels [9].

The relationship between specimen size and DT energy for fully plastic fracture has been investigated and is discussed in a later section concerning the DT test. The point here is that the section-size effect can be complicated when the transition features in the fracture resistance of a material are being determined with a subthickness specimen. Linear elastic fracture mechanics is most useful in defining fracture resistance in the plane-strain regime and in the elastic-plastic regime. When extensive through-thickness yielding occurs, however, the width and thickness of the specimen limit the size of the plastic zone. The criterion used as a measure of fracture resistance then becomes a three-dimensional parameter, and the value obtained in a fracture test is a function of the geometry of the test piece.

Effects of Stable Crack Extension

The translation into structural performance of empirical criteria for high levels of fracture resistance involves more than a correlation with stress and flaw size. When extensive through-thickness yielding precedes fracture, a small crack-front extension can occur without triggering an unstable condition. Continued extension of the crack is then dependent upon a continued input of plastic overload energy. Therefore, the fracture mode and the propagation rate under such conditions are dependent upon the configuration of the structure surrounding the flaw and the nature of the overload being experienced.

When a material has a high level of fracture resistance, pop-in flaws can be arrested, and any flaw can grow until the stress in the net section of the load-bearing member exceeds the yield strength or the limit load condition. A guarantee of limit load performance in the presence of a through-thickness flaw would be sufficient evidence to certify an adequate level of integrity for most structures. Although it is of primary importance, material selection is only one aspect of a structural integrity analysis, which also includes trade-offs in design refinement, fabrication quality, and inspectability.

Certain structures, such as gas linepipes, require the material to withstand a plastic overload in order to attain an acceptable level of structural integrity. For other types of structures, fracture in a critical region may be load, strain, or energy dependent. Experimentally, the level of fracture resistance needed to achieve an acceptable level of

reliability can be determined most economically by empirical correlation with full-scale tests. In the design stage, finite element analysis can provide useful information on peak strain levels in a structural detail; but translation of fracture resistance criteria into structural performance outside the plane-strain regime remains an empirical exercise.

CHARPY V-NOTCH TEST (ASTM E23)

Two of the most overworked words that make the semantics of impact testing confusing to many people are *Charpy* and *Drop Weight*. Because of the proliferation of specimens and criteria for fracture resistance that use these generic terms, some clarification is in order. About the only thing that the impact tests using these prefixes have in common is a three-point bending load. The term *Drop Weight* indicates, however, that testing is by impact, and the parameter used for fracture resistance is the appearance of the fracture, whether ductile or brittle.

The Charpy test is the oldest standardized impact test in general use (E23-33T). Although there are several specimen designs, the most commonly used specimen today is the 10-mm-square specimen with a notch 2 mm deep having a 0.25-mm root radius. The C_v test has served well in the past for comparing certain materials, but translation of C_v energy to structural parameters is made on a case-by-case basis.

The C_v energy criterion provided the first correlation between the results of a laboratory fracture test and the service performance of the material in a structure. The correlation of C_v energy and the initiation, propagation, and arrest of fractures in the World War II Liberty ships and T-2 tankers is shown in Fig. 1. Fractures initiated from small flaws when the C_v energy was less than 14 J (10 ft-lb), and arrested cracks were found only when the C_v energy was more than 27 J (20 ft-lb). These correlations have been used to justify the use of a 20-J (15 ft-lb) criterion to preclude brittle fracture in all types of welded steel structures. Unfortunately, the 20-J (15 ft-lb) criterion was found to be a unique criterion that could predict a certain level of structural performance in only a few steels.

All steels have a very low level of fracture resistance when their C_v energy value is less than 20 J (15 ft-lb). Higher C_v energy values imply higher levels of fracture resistance, but this criterion does not necessarily index the start of the transition region to higher levels of fracture resistance, which was the case for the ship steels in Fig. 1. For this reason, other criteria of fracture resistance, such as percent shear and lateral expansion, have been promoted as parameters that are more generally indicative of structural performance [3,10].

Numerous papers have been written on the problems that arise when attempts are made to develop a correlation between structural performance and any criterion of fracture resistance derived from the Charpy test [3,4,8,11-13]. The difficulty does not stem from the criterion used for fracture resistance, because all criteria reflect the amount of ductility that occurs prior to fracture which is related to the geometry of the test piece. Therefore, the various criteria that have been proposed are all proportional to each other. The dilemma of the C_v test is not caused by the criterion used for fracture resistance, but it is due to the design of the test piece.

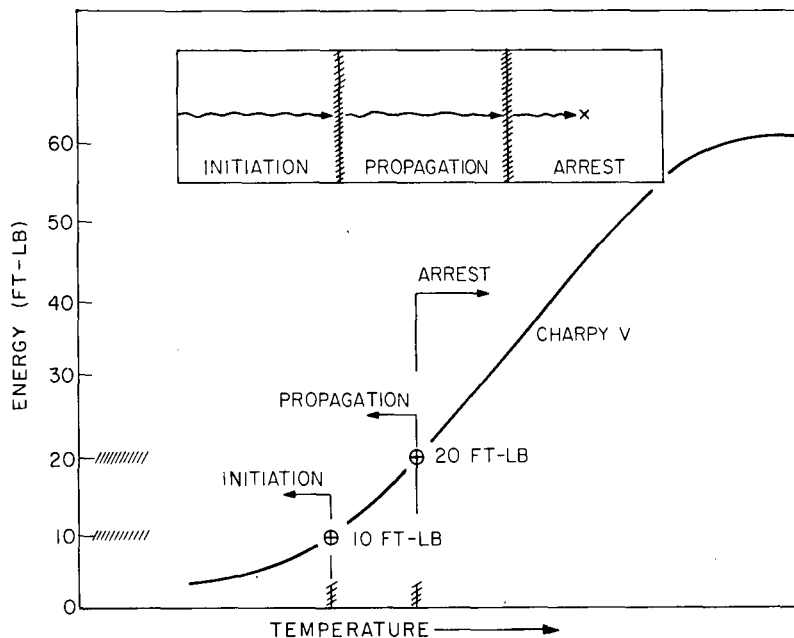


Fig. 1 — Correlation of World War II ship fractures with C_V energy values

The relatively dull notch in the standard C_V specimen is one reason the transition region of a C_V energy-temperature relationship is not in phase with structural performance. To improve this feature of the C_V specimen design, much recent research has been conducted with fatigue-cracked C_V specimens. Fatigue cracking the C_V specimen tends to steepen the transition region and shift it to a higher temperature, but the plane-strain measuring capability of a 10-mm section remains at $2.0\sqrt{\text{mm}}$ ($0.4\sqrt{\text{in.}}$) = K_{Id}/σ_{yd} . This limitation in plane-strain measurement can be an important restriction to the characterization of the transition region of certain steels.

The dynamic plane-strain fracture toughness in some steels at the toe of the transition region becomes nearly constant at the $K_{Id}/\sigma_{yd} = 2.5\sqrt{\text{mm}}$ ($0.5\sqrt{\text{in.}}$) level, which is the constraint level of a section 16 mm ($5/8$ in.) thick. For such materials there is a big shift in the temperature of the transition region when the constraint conditions are slightly less than this critical level. The effect of insufficient constraint in the transition region is illustrated by the data in Fig. 2, where the influence of notch sharpness and section size on the temperature transition features of an AISI 601 steel heat treated to 960 MPa (140 ksi) yield strength are substantial. Note that the transition region in the curve for the fatigue-cracked Charpy specimen, the C_V -energy/area curve, is significantly steeper than the transition region in the curve for the standard C_V specimen. Note also that the curve for the precracked 10-mm Charpy specimen is displaced approximately 33°C (60°F) lower in temperature than the curve for the 16-mm DT specimen. Unfortunately, these displacements in the energy temperature relationships obtained from 10-mm and 16-mm specimens, respectively, are not predictable from steel to steel. Therefore, when the 10-mm C_V specimen is a subthickness specimen, care must be exercised in interpreting energy values in the transition (mixed-mode) region. This is also true for a 16-mm DT specimen, but the analyses of energy values from the DT test are more reliable.

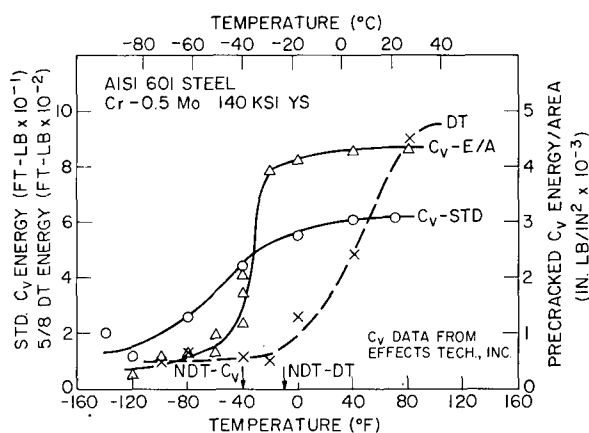


Fig. 2 — Comparison of the temperature transition characteristics of an AISI 601 steel using the standard C_V test, the fatigue-precracked C_V test, and the 16-mm (5/8-in.) DT test. Note that the curves for the two sets of C_V test data are displaced to lower temperatures than that for the DT data.

DROP WEIGHT-NIL DUCTILITY TRANSITION (NDT) TEMPERATURE TEST (ASTM E208)

Because of the difficulty and expense of developing correlations between C_V energy and the structural performance of every ferritic steel, the Drop Weight-Nil Ductility Transition (NDT) temperature test was devised at the Naval Research Laboratory in the early 1950s [15]. This test is currently covered by ASTM E208, and it was the first test to be called a Drop Weight test. This term was used to emphasize the simplicity of the test which could be used to determine the temperature at which a steel sample can plastically deform under a dynamic load in the presence of a small crack. It was also the first pop-in crack test.

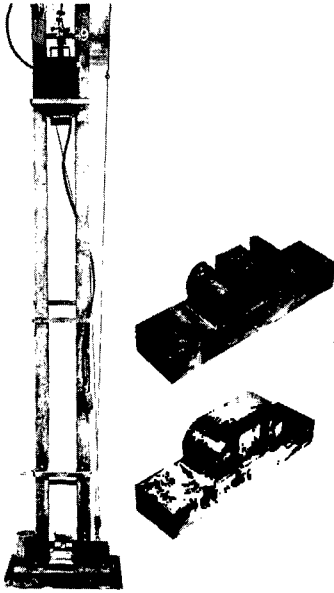
The pop-in crack of the DWT-NDT specimen is formed when a brittle weld bead fractures as the specimen is loaded in a drop-weight machine (Fig. 3). The crack from the weld bead is either arrested or it continues to propagate across the top surface of the specimen. If the crack does not propagate to one of the top corners of the specimen before the surface strain approaches 2%, the deformation is stopped by an arrestor block on the anvil and the test result is called a “no break.” Specimens are subsequently tested at lower temperatures until a “break” occurs. The DWT-NDT test is, therefore, a “go — no-go” appearance test.

The interpretation of structural performance at the NDT temperature is self-explanatory, but the NDT temperature index can also provide a broader projection of structural performance when certain generalities occur in the transition features of a steel. These generalities in the transition features of conventional steels were the first seen from the results of the C_V test and the explosion bulge test [4].

Explosion Bulge Test

The explosion bulge test was designed to simulate a large structural element being subjected to a dynamic, plastic overload. Because of the size of the original specimen, 356 × 356 × 25 mm (14 × 14 × 1 in.), the plate is loaded by an explosive charge. The

TEST EQUIPMENT



SPECIMEN SERIES

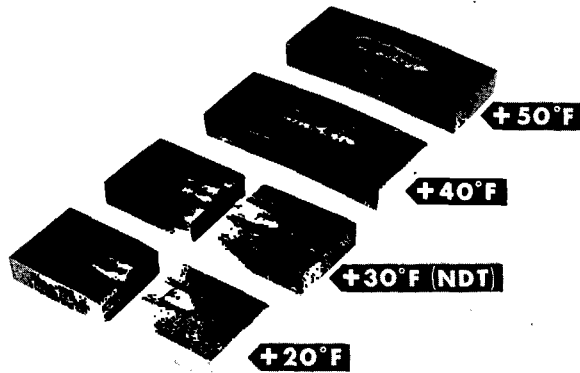


Fig. 3 — The drop-weight machine and a series of specimens illustrating the break- no-break performance at the Nil Ductility Transition (NDT) temperature

plates are conditioned to the desired test temperature, placed on a die with a circular hole, and an explosive charge is then detonated above the plate surface at a stand-off distance of 305 mm (12 in.) or more. With this technique, the air transmits a shock wave that causes an inertial loading of the plate and a strain rate in the material comparable to that in the DWT-NDT test. In Fig. 4 is shown a series of plates tested at various temperatures in the transition region, three critical temperatures are noted.

Critical Temperature Concept

When a series of 25-mm (1-in.) thick plates of steel are tested in the bulge test, the temperatures for three critical levels of performance can be established. The temperature below which a plate fractures in a brittle (nil-ductile) manner is called the NDT temperature. Approximately midway in the transition region, fractures are arrested at the hold-down region. This performance is called Fracture Transition Elastic (FTE) because plastic overloading is required to propagate the fracture at temperatures above the FTE. The "upper shelf" temperature of the transition region is called Fracture Transition Plastic (FTP) because at temperatures above the FTP no cleavage fracture occurs and the plate is fully plastic.

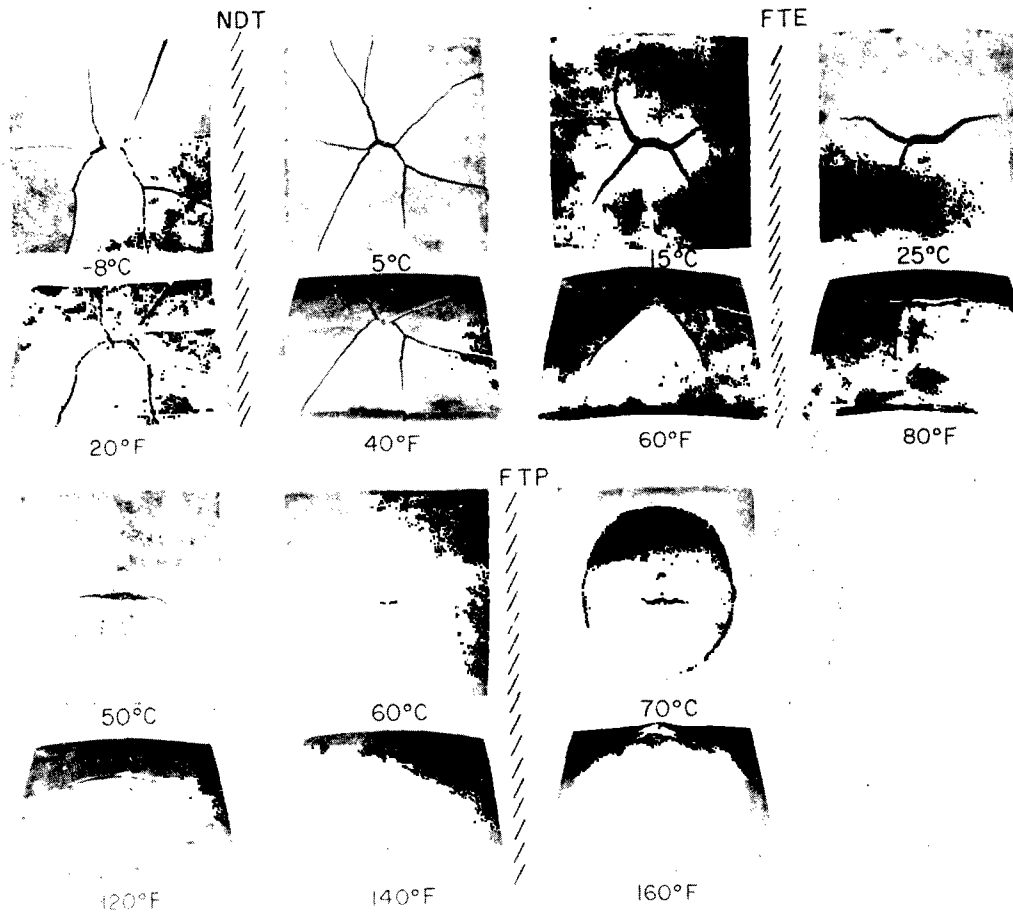


Fig 4 — Performance of a ship plate steel in the Explosion Crack Starter test. The steel illustrated features a 20-J (15 ft-lb) C_v transition of approximately 0°C (30°F).

The three critical temperatures, NDT, FTE, and FTP, usually occur approximately at 33°C (60°F) increments for conventional, low-strength structural steels. On the basis of this observation and the analysis of many structural failures, a generalized Fracture Analysis Diagram (FAD) was proposed in 1963 by Pellini (Fig. 5). The FAD is indexed to the NDT temperature and to a relative yield stress ratio [15]. The diagram was later modified to apply to steel in sections 76 to 305 mm (3 to 12 in.) thick; thus, the critical temperature concept could be scaled for size effects. Since 1960 FAD has been the only engineering tool for translating the results of a laboratory fracture resistance test to structural performance, and only recently has LEFM been developed to the stage where it could be considered an analytical approach to a structural analysis for fracture.

The DWT-NDT test is simple to conduct, but the DWT-NDT test and the interpretation of structural performance from the test result have certain limitations. The test may not apply to cold-worked material or to quenched-and-tempered steels because of the

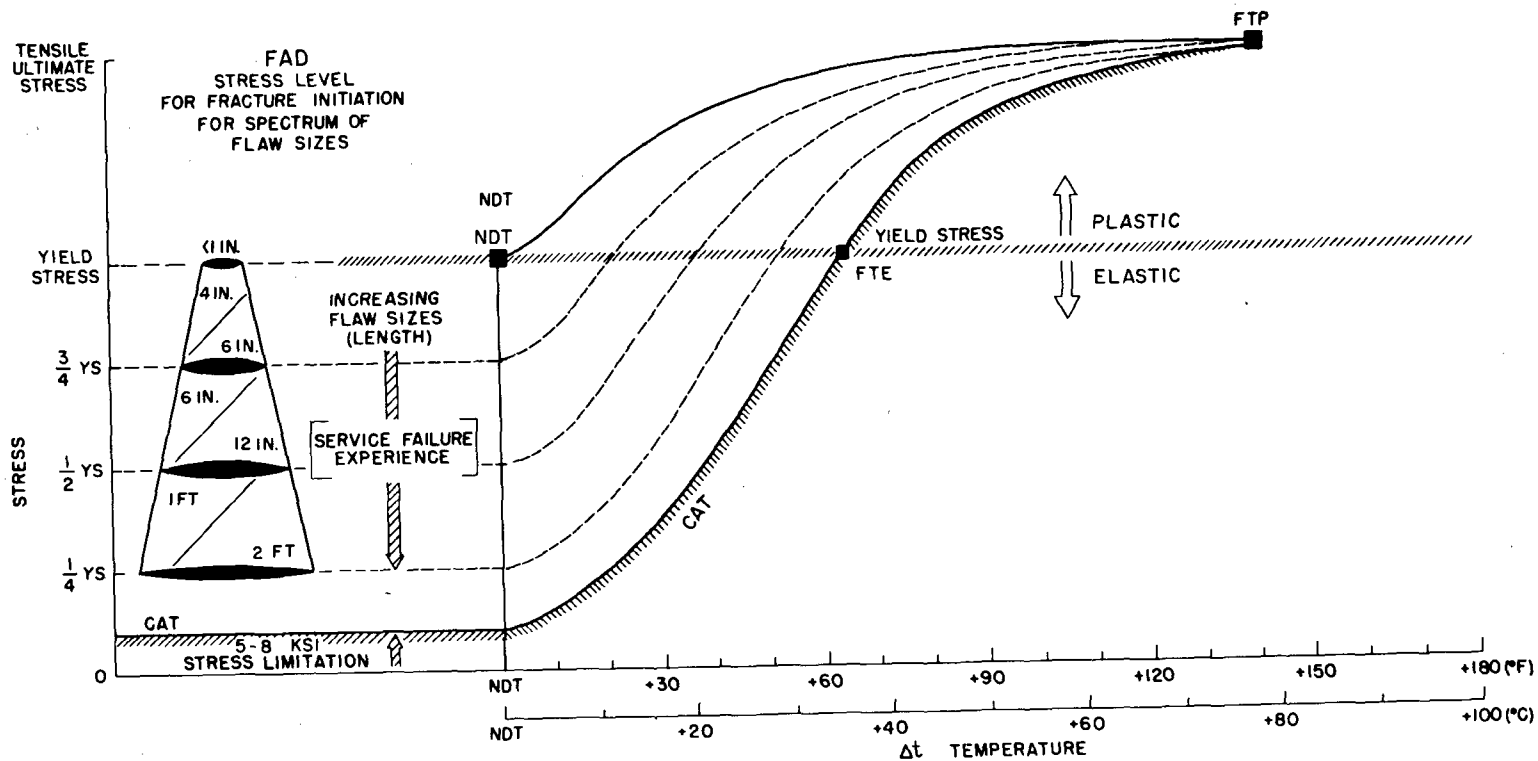


Fig. 5 — Fracture Analysis Diagram (FAD) illustrating a generalized relationship between flaw size, effective stress, and temperature for steels in their transition region

potential for a crack arrest in the heat-affected zone of the specimen. Also, the heat from welding on the brittle crack starter bead may adversely modify, or in some cases enhance, the base metal properties. Like the 20-J (15 ft-lb) C_v criterion, the NDT temperature implies a boundary condition for brittle performance.

The critical temperature concept implies that fracture resistance increases rapidly at increments above the NDT temperature. Unfortunately, this is not true for all of the conventional structural steels because in some steels fracture resistance increases very slowly above the NDT temperature; other steels have a low fracture resistance even at upper shelf temperatures. These limitations being recognized the critical temperature concept can still be a useful tool for referencing specific levels of performance in the temperature transition region.

Perhaps the most important function of the DWT-NDT test is to provide a reference index to the plane-strain fracture limit for sections 16 mm (5/8-in.) thick. If one is familiar with the test method, he can readily recognize that an NDT performance translates to brittle fracture initiating from a small flaw. This level of fracture resistance in LEFM terms is [9]

$$K_{Id}/\sigma_{yd} = 2.5\sqrt{\text{mm}} \ (0.5 \sqrt{\text{in.}}).$$

Service experience has shown that when the steel in welded structures has a fracture resistance less than this critical value, catastrophic fractures can be expected.

The NDT temperature is not a size-dependent parameter, because the standardized test procedure fixes the flaw size by specifying the size of the weld bead and fixes the stress level by loading to the yield stress. Naturally, if these mechanical conditions are changed, plane-strain fracture can occur at temperatures other than the NDT temperature. There is, however, a lower size limitation to the determination of an NDT temperature, namely, the requirement that the test specimen be at least 16 mm (5/8-in.) thick. Sections thinner than 16 mm (5/8 in.) may fracture in a brittle, plane-strain manner, but they do not have an NDT temperature.

The semantics of the term NDT temperature are sometimes mixed with a Plane-Strain Limit temperature, but the fracture resistance level at the NDT temperature refers to the mechanical conditions defined in ASTM E208. The restriction of the NDT temperature to relatively thick sections provided part of the incentive for the standardization of another test method that could locate the temperature transition region of steel in thin sections using a fracture appearance criterion. This test is the Drop-Weight Tear Test.

DROP-WEIGHT TEAR TEST (ASTM E436)

The Drop-Weight Tear Test (DWTT) is used to define the temperature transition region for ferritic steels in sections from 3.18 to 19.1 mm (0.125 to 0.75 in.). Its primary application has been to determine the temperature at which shear-type fractures occur in steel for linepipe. For many pipes, the propagation of cracks that can be initiated from a number of accidental sources will run for extended distances unless the appearance of the

fracture is more than 80% shear. Although this criterion indexes the performance of linepipes of certain designs, the test and its fracture appearance criterion do have general application for establishing the transition region for steels in thin sections that are not necessarily used in linepipes.

When a conventional steel having a yield strength under 827 MPa (120 ksi) is used in sections less than 16 mm (5/8 in.) thick, the transition in fracture resistance tends to be restricted to a narrower range of temperatures than when the same steel is rolled to a thicker gage. Therefore, for many structural applications, a fracture appearance criterion is all that is needed to predict a brittle or ductile performance because of the narrow range of temperatures involved. This is illustrated in Fig. 6, where the transition region in a 9.4-mm (3/8-in.) thick plate of A-36 steel is only 11°C (20°F) from the toe to the 80% shear index. Fracture resistance rises so sharply in thin sections that a 50% shear temperature criterion is a very readily determined and unambiguous parameter for predicting service performance when a full-section specimen is used.

Because the DWTT has a fracture appearance criterion, it is not a test for generalized use. It cannot be used to establish fracture resistance quantitatively at upper shelf temperatures or to evaluate transitions for steels that do not undergo a sharp transition in fracture appearance. Energy measurements from the DWTT are not meaningful because the small notch causes the ligament to deform plastically prior to fracture even when the fracture is brittle. Although the test has its limitations, it is useful for indexing the temperature transition region for plain carbon and low-alloy steels in sections thinner than 19 mm (3/4 in.).

DYNAMIC TEAR TEST (MIL-STD (SHIPS) 1601)

The Dynamic Tear (DT) test was developed to fill the need for a practical test that could precisely measure fracture resistance over a broad range, including that encountered in the transition region of the ferritic steels. For practical reasons the specimen is not instrumented, and the total energy used to fracture a specimen is the criterion of fracture resistance. This empirical value of fracture resistance, DT energy, is translated into structural parameters by correlation with an analytical parameter or with specific structural performance.

The primary intent in developing the DT test was not to develop an inexpensive K_{Ic} or K_{Id} test but to provide a more sensitive and reliable fracture-resistance criterion for the elastic-plastic and plastic regimes. Although the DT energy criterion is empirical, it has correlated very well with K_{Ic} values for various steels, titanium, and aluminum alloys [3,16-18]. The correlations cover a sufficiently broad range of alloys in each base metal to justify the development of generalized diagrams for structural analysis. The diagrams are called Ratio Analysis Diagrams, where by a simple graphical procedure a DT energy value can be translated into a K_{Ic}/σ_{ys} value or a critical flaw size, as will be described later.

When practical, the DT test uses a full-thickness specimen so that the constraint in the specimen is the same as that in the structural element of interest. Obviously, this is

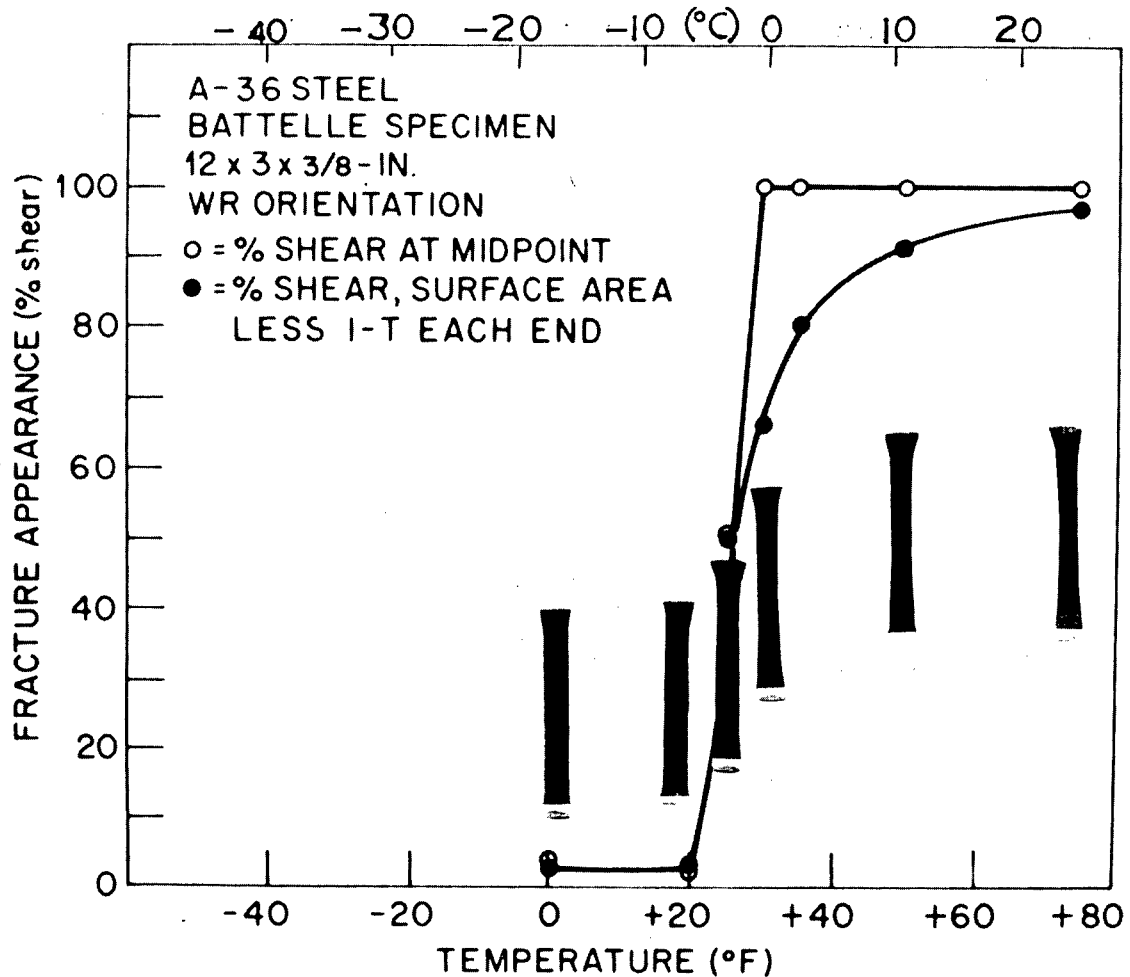


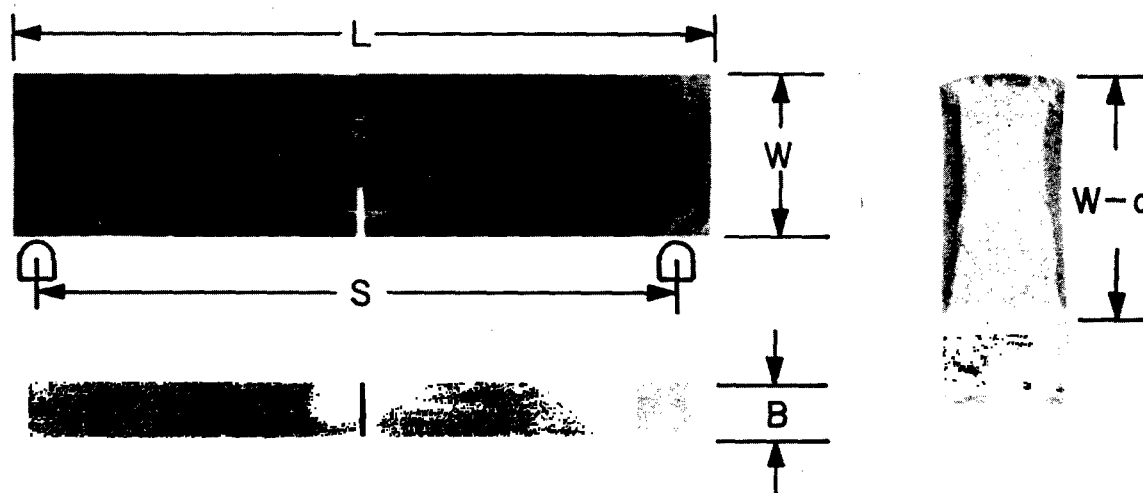
Fig. 6 — A typical temperature transition for fracture appearance in the Drop-Weight Tear Test (DWTT). Note the narrow transition region from a cleavage to a shear fracture mode for both the area and the linear method of measurements.

not very practical when thick sections are involved, so extensive studies have been conducted to establish procedures to compensate for the effect of specimen size. These studies have included tests on 12-in.-thick sections, and methods for extrapolating DT energy values obtained with a subsize specimen to full-section structural performance have been developed [4,9].

Specimen Design

The experience, gained in early work concerning the effects of constraint on the temperature transition features of steels, indicated that for standardization purposes a minimum

subsize DT specimen should be 16 mm (5/8 in.) thick. The next critical dimension in the design of a specimen for general use is the notch depth. This was set at 0.6 times the thickness to preclude the plastic hinge in ductile materials from reaching the top surface. Another important design feature is the net section, or ligament, which was set at 2 times the thickness, as shown in Fig. 7. This ligament design allows extensive stable crack extension to occur so that a normal V-shaped crack front can develop in materials when fracture is preceded by extensive through-thickness deformation. If these basic principles are incorporated in the design of the DT specimen, the DT test method can be economically applied to any structural metal. The test method was standardized in 1973 as MIL-STD 1601; a modification of the MIL-STD test method appears in Vol.10 of the 1975 *ASTM Book of Standards* as a Recommended Practice.



DIMENSIONS OF 5/8-in. (16 mm) DT SPECIMEN

	L	S	W	W-a	B
in.	7	6.5	1.6	1.125	0.625
mm	181	165	38	28.5	16

Fig. 7 — The 16-mm (5/8-in.) Dynamic Tear (DT) specimen. The dimensions are shown in millimeters. The standard DT test is defined in MIL-STD 1601.

Analysis of DT Energy

K_{Ic} Versus DT Energy—The empirical nature of a criterion for fracture resistance in terms of the energy needed to fracture a specimen in an impact test complicates a direct analytical treatment of DT data. This is not a permanent limitation, however, because

translations can be generated by correlations with the more basic parameters, such as K_{Ic} or K_{Id} , as previously stated. The first correlation between K_{Ic} and DT energy was developed with high-strength steels that were not sensitive to strain rate [18]; The initial relationship, which was developed with wrought products, was later substantiated by data developed by Groves and Wallace for the Steel Founders' Society of America, using high-strength cast steels [19]. The data from the study on cast steels are shown plotted on the original relationship developed with wrought steels in Fig. 8. The correlation extends to a K_{Ic} value of 110 $\text{MPa}\sqrt{\text{in.}}$ (100 $\text{ksi}\sqrt{\text{in.}}$), where the 16-mm (5/8-in.) DT specimen becomes elastic-plastic and the DT energy increases at a more rapid rate than does the plane-strain parameter for fracture toughness (K_{Ic}).

A correlation between K_{Id} and DT energy for the conventional structural steels remains in the developmental stage. These materials are strain-rate sensitive, and this characteristic has always complicated attempts to measure their fracture resistance properties in terms of K_{Id} . If conditions are such that fracture initiates by cleavage, then the fracture resistance is low; if the fracture initiates by microvoid coalescence, then the fracture resistance is high. Therefore, the fracture mode must be consistent for the two test methods or an inaccurate correlation will be developed. In addition, the strain rates associated with impact testing are sufficient to cause complex bending waves in the specimen, which makes the analysis of K_{Id} tests difficult [5,7]. Until more K_{Id} measurements are made, empirical correlations are the only means of providing a correlation between K_{Id} and DT energy.

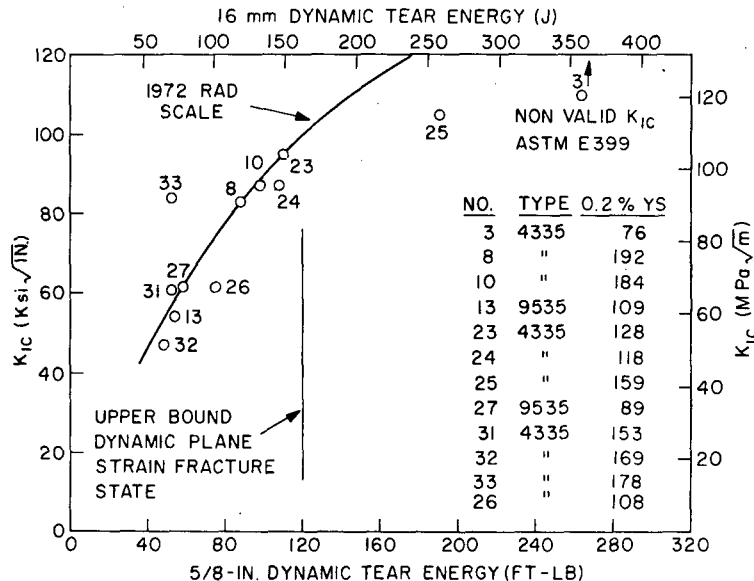


Fig. 8 — Correlation between K_{Ic} and 5/8 DT energy for high-strength wrought and cast steels. The data for the cast steels are from Groves and Wallace [19].

K_{Id} Versus DT Energy—When the fracture in a DT specimen initiates and propagates under plane-strain conditions, the fracture propagates completely through the specimen very fast. At nominal impact velocities, the energy in the initial dynamic shock is sufficient to load the specimen up to a yielding condition. If additional energy is required, fracture may be considered no longer a plane-strain type because some plastic overload was required to initiate fracture. These two conditions are illustrated in Fig. 9 by the force vs time traces from an instrumented tap striking the specimen at 8.5 m/s (28 ft/s). Because the plane-strain limit for a 16-mm (5/8-in.) specimen occurs when $K_{Id} = 2.5\sqrt{\text{mm}}$ ($0.5\sqrt{\text{in.}}$) σ_{yd} , this fracture resistance level is equivalent to that at the NDT temperature. These basic principles of LEFM and the performance characteristics of various steels in the NDT and DT tests can be used to develop a relationship between K_{Id} and DT energy.

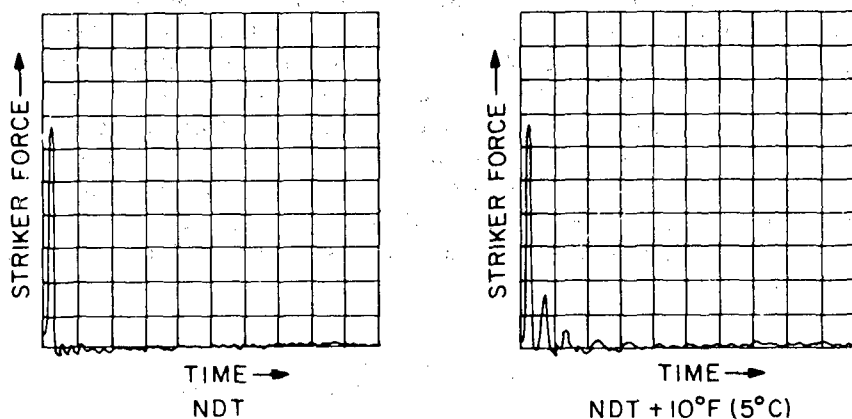


Fig. 9 — Illustrating the appearance of force-time traces from an instrumented trip breaking 5/8 DT specimens at the NDT temperature of steels

The DT energy, at the NDT temperature, of 22 different steels ranging in yield strength from 207 to 965 MPa (30 to 140 ksi) is shown plotted as a function of static yield strength in Fig. 10. Some of the NDT temperatures were determined with ASTM E208 procedures, and some were deduced from the appearance of the force vs time traces as described above. Scatter was expected in the data because of the nature of the two test methods. Dynamic tear energy at the NDT temperature can be converted to dynamic fracture toughness K_{Id} by the use of the above relationship and the equation

$$\sigma_{yd} = \sigma_{ys} + 30 \text{ ksi (207 MPa)}$$

to convert the static yield strength to the dynamic yield strength. The relationship between K_{Id} and DT energy, calculated from the average DT energy values in Fig. 10, is compared to that developed for high strength steels in Fig. 11.

There are apparently two correlations between plane-strain fracture toughness and DT energy, depending upon the dominating microfracture mode. When the microfracture mode is predominantly microvoid coalescence, slightly higher K_{Ic} values correspond to a certain DT energy value rather than to the K_{Id} value where the microfracture mode is predominantly cleavage. The lower K_{Id} -DTE relationship in Fig. 11 was calculated from DTE values for various steels at their NDT temperature or under conditions assumed to

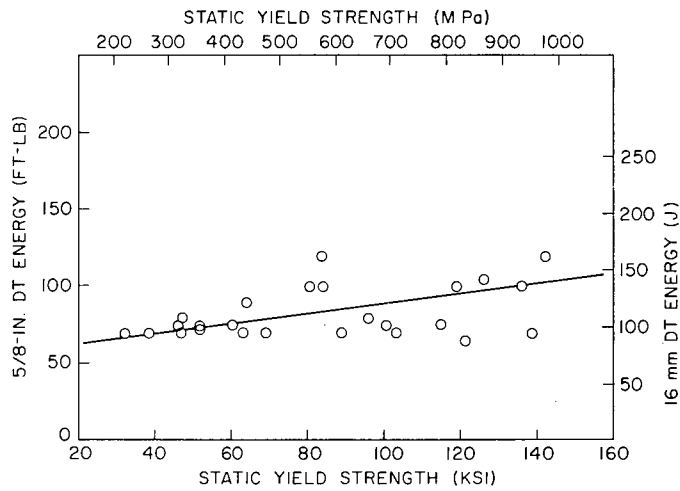


Fig. 10 — Relation between 5/8 DT energy at the NDT temperature and the static yield strength of steels

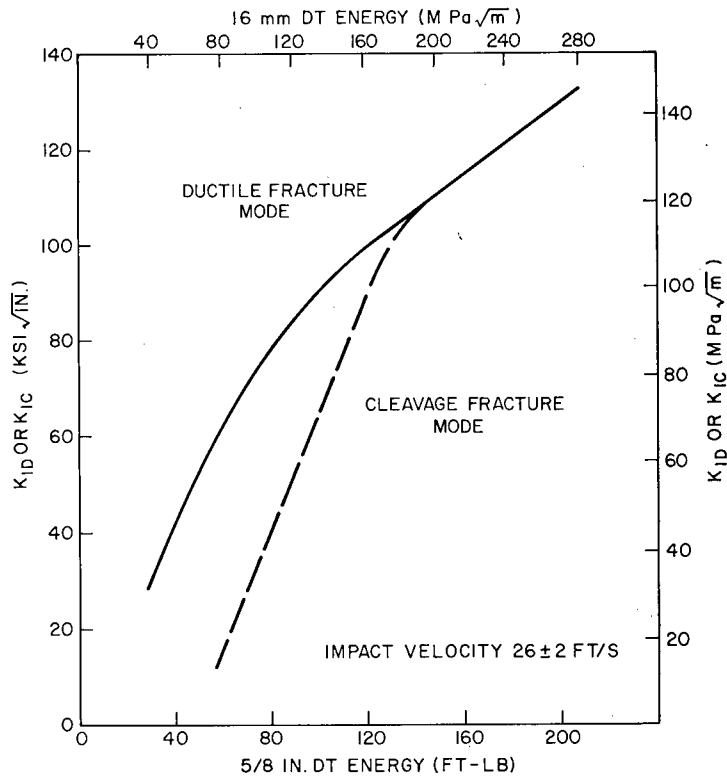


Fig. 11 — The relationships between DT energy and the plane-strain stress-intensity factors K_{IC} and K_{ID} . For steels at their upper shelf temperatures use the K_{IC} relationship, and for steels at temperatures within the transition region use the K_{ID} relationship.

be the plane-strain limit for a 16-mm (5/8 in.) section where the fracture resistance can be expressed as [18]

$$(K_{Id}/\sigma_{yd} = 0.5 \sqrt{\text{in.}} \quad (2.5\sqrt{\text{mm}}).$$

Hopefully, this preliminary relationship can be more firmly established when valid dynamic J_{Id} or K_{Id} data become available from dynamic tests using large instrumented specimens.

DT Energy and Specimen Size — The energy measured in a DT test can be related to specimen size and shape when fracture takes place after the ligament becomes plastic. The power law relationship that equates DTE to the geometry of the specimen is

$$\text{DTE} = R_p (b)^2 (B)^{1/2} \quad (2)$$

where

- DTE = dynamic tear energy
- R_p = plastic resistance factor
- b = ligament
- B = thickness.

This relationship has been validated for four different aluminum alloys, 5083, 5086, 6061, and 7005, and for a wide variety of steels, including some 152-mm (6-in.)-thick plates of A533 steel [19]. Unfortunately, the effect of specimen size on the DTE of titanium alloys was consistent only for limited ranges within the whole alloy system.

DT Energy and Structural Analyses — The most useful application of Eq. (2) is to provide a structural analysis for DTE values obtained from specimens that are different in size from the standard specimen. From Eq. (2), and equivalent 16-mm 5/8-in. DTE can be calculated, and the appropriate RAD can be drawn to obtain a structural performance analysis [17]. For example, if the geometry of a 25-mm (1-in.) thick component is such that only a specimen 9.6 mm (3/8 in.) can be removed for a DT test, Eq. (2) can be used to convert the DT value from this specimen to an equivalent 16-mm (5/8-in.) value. The equivalent value is then positioned on the 25-mm (1-in.) RAD, as shown in Fig. 12, and a structural analysis is thereby derived. Projecting the performance of the same material in sections other than those that are 25 mm (1 in.) thick requires shifting the elastic-plastic region up or down in accordance with the conditions defined as follows:

$$\begin{aligned} \text{(L) Plane-Strain Limit:} \\ B = 2.5 (K_{Ic}/\sigma_{ys})^2 \end{aligned} \quad (3)$$

$$\begin{aligned} \text{(YC) Yield Criterion:} \\ B = 1.0 (K_{Ic}/\sigma_{ys})^2 \end{aligned} \quad (4)$$

where B = thickness of the section. The mechanical conditions defined by Eqs. (3) and (4) are arbitrary definitions of critical performance levels, but they are useful indexes for evaluating the results of trade-off studies and for assessing the effects of improving metal quality on structural performance [9].

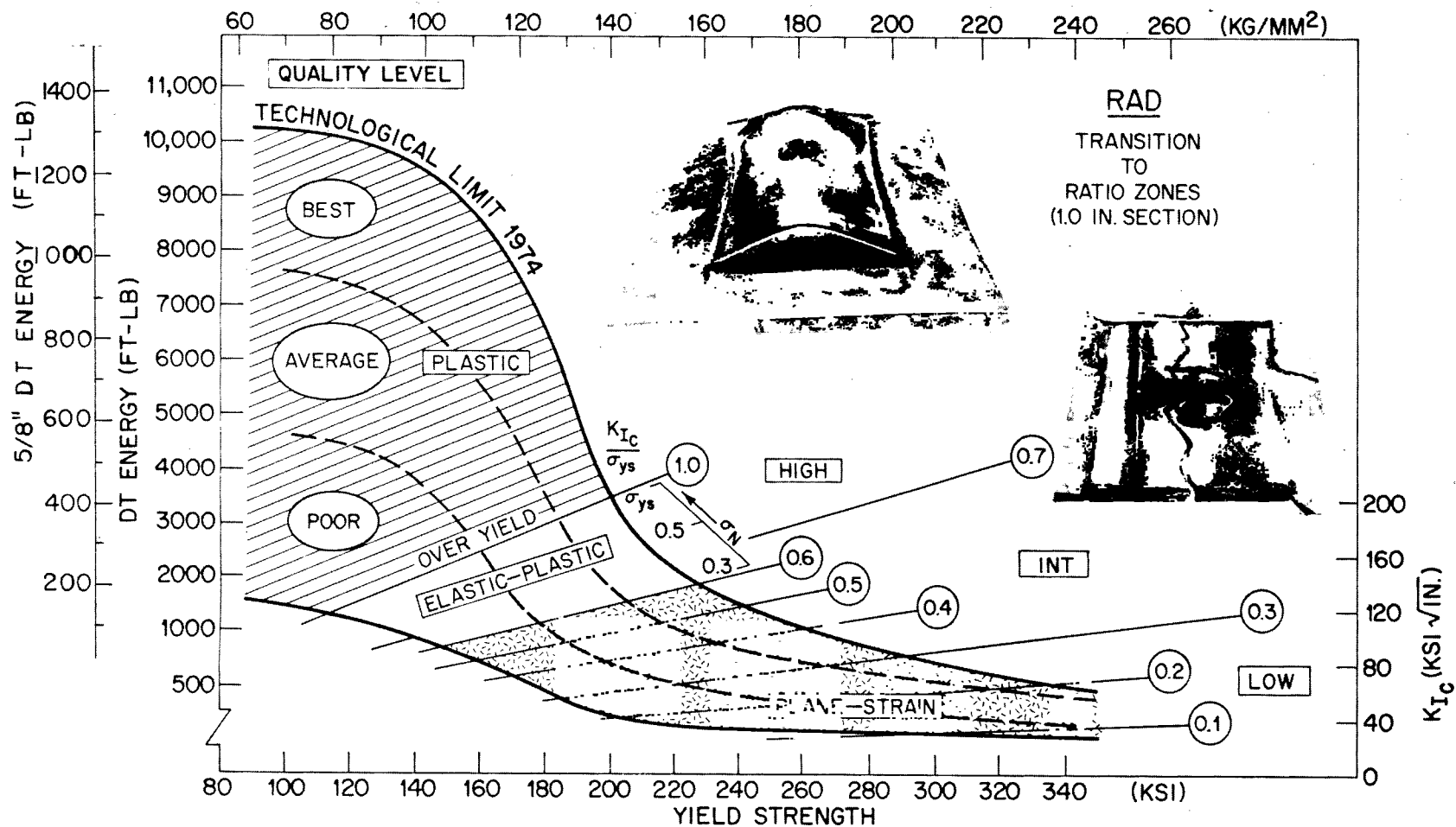


Fig. 12 — The Ratio Analysis Diagram (RAD) for the steels. The position of the elastic-plastic regime is illustrated for a 25-mm (1-in.) thick section.

Section Size and Elastic-Plastic Analyses — The effect of constraint on the slope of the fracture resistance vs temperature curve as it enters the elastic-plastic regime for ferritic alloys is complex. Certain generalities have been proposed for the extrapolation of size effects using a generalized K_{Id}/σ_{yd} vs temperature curve, such as the upper bound curve in Fig. 13. There are exceptions to this generalized shape for defining the upper bound of dynamic plane-strain fracture resistance, and the temperature transition characteristics of a material of interest should be generated. Unfortunately, the more flexible analytical parameters, such as J_d , are also size dependent when the plastic zone extends through the ligament of the specimen. Therefore, at this time, elastic-plastic fracture mechanics is in the research stage of development, and the interpretation of fracture resistance data from subsize specimens to full-section performance remains an empirical exercise.

The complexity of an analytical treatment of fracture resistance of steels in the transition region has been recognized, and several practical approaches for translating size effects in the elastic-plastic region have been suggested. One way to adjust a 16-mm (5/8-in.) DTE vs temperature relationship to that for a thicker section is to establish the temperatures for the L and YC indexes for the section of interest. The appropriate DTE values for the L and YC indexes can be obtained from Eqs. (3) or (4) and Fig. 13. For sections up to 75 mm (3 in.) thick, no temperature adjustment is necessary for the L index, but the temperature for the YC index of the thicker section on the 16-mm (5/8 in.) DTE temperature curve is shifted to a higher temperature by the following increments:

Thickness, mm (in.)	25 (1)	50 (2)	75 (3)
°C	6	22	28
°F	10	40	50

Details on the use of this and other approaches to an analysis for size effects in the temperature transition region are presented in Ref. [9].

SUMMARY

The development of LEFM has helped to clarify the interrelationship between the mechanical and the metallurgical aspects of fracture, including the effects of constraint on the fracture mode and the transitions in fracture resistance of the structural metals. The elastic-plastic portion of transition regions can now be defined in terms of LEFM parameters; by correlation, the results obtained from the empirical impact tests can provide a much-needed structural analysis in this important regime between brittle and ductile performance.

The DT test was designed to overcome some of the limitations of the C_v test and the DWT-NDT test. The DT specimen has an extended ligament compared to the ligament in a C_v specimen or a K_{Ic} specimen. This feature increases the sensitivity for measurement of fracture resistance in the elastic-plastic regime by allowing a larger plastic zone to develop.

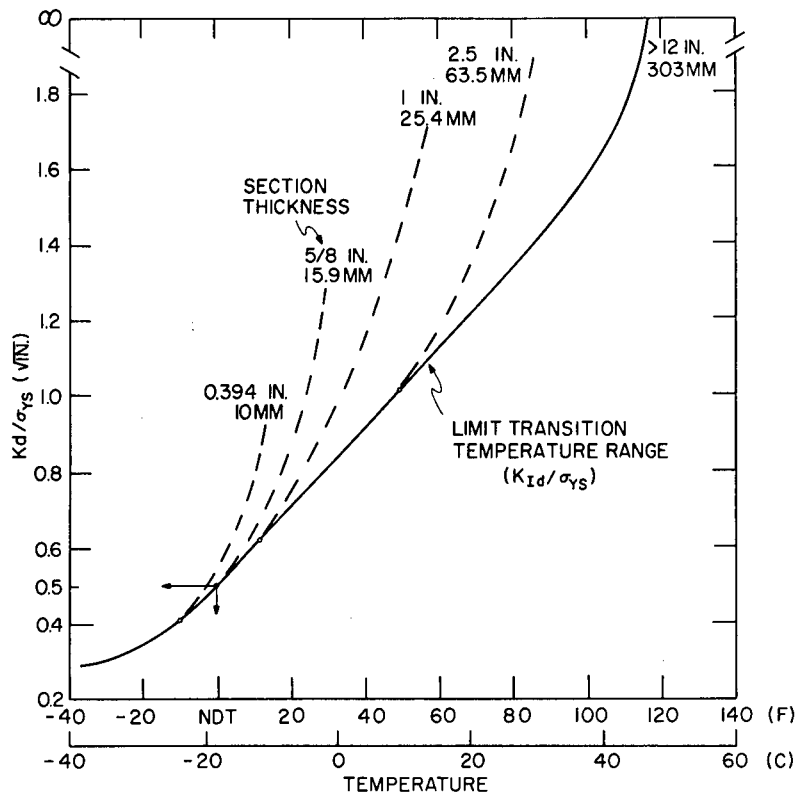


Fig. 13 — The Limit-Transition-Temperature-Range (LTTR) for an A-533 steel. The start of the transition curves for subsize specimens is illustrated to indicate the effect of size on the fracture resistance of steels in the transition region.

Impact testing of the DT specimen introduces a high enough strain rate to simulate effectively the high strain rate of a natural pop-in crack that may occur in service. Thus the upper bound of the temperature transition characteristics of the ferritic alloys can be established for a structural reliability analysis. Although more research needs to be conducted on size effects, the economics of conducting a DT test and the availability of initial correlations with the more basic fracture mechanics parameters should help in the application of fracture mechanics to design.

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REFERENCES

1. "Notched Bar Impact Testing of Metallic Materials," ASTM Standard Method E23-72.
2. "Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels," ASTM Standard Method E208-69.
3. "Impact Testing of Metals," ASTM STP 466, March 1970.
4. W.S. Pellini, "Evolution of Engineering Principles for Fracture-Safe Design of Steel Structures," NRL Report 6957, Sept. 23, 1969.
5. G.E. Nash and E.A. Lange, "Mechanical Aspects of the Dynamic Tear Test," Trans. ASME, J. Basic Engrg., D91, 535-543 (Sept. 1969).
6. A.K. Shoemaker and S.T. Rolfe, "The Static and Dynamic Low-Temperature Crack Toughness Performance of Seven Structural Steels," Engrg. Fracture Mechanics, 2, 319, 1971.
7. C.A. Griffis, F.J. Loss, and J.R. Hawthorne, "Measurement of Plane-Strain Fracture Toughness at High Loading Rates," Report of NRL Progress, 34-36 Aug. 1975.
8. G.R. Irwin and R. Roberts, "Fracture Toughness of Bridge Steels," Phase I Report, Lehigh University, July 1972.
9. W.S. Pellini, "Analytical Design Procedures for Metals of Elastic-Plastic and Plastic Fracture Properties," Welding Research Council Bull. 186, Aug. 1973.
10. "Mechanical Testing of Steel Products," ASTM Standard Methods and Definitions A370-74.
11. M.L. Williams, "Analysis of Brittle Behavior in Ship Plates," Symposium on Effect of Temperature on the Brittle Behavior of Metals with Particular Reference to Low Temperatures, ASTM STP 158, 1954, p. 11.
12. P.P. Puzak and E.A. Lange, "Significance of Charpy-V Test Parameters as Criteria for Quenched and Tempered Steels," NRL Report 7483, Oct. 10, 1972.
13. H. Czyzewski, "Brittle Failure: The Story of a Bridge," Metal Progress/West, 1, No. 1, 6-12 (Mar. 1975).
14. "Drop-Weight Tear Tests of Ferritic Steels," ASTM Standard Method E436-71T.
15. P.P. Puzak, A.J. Babecki, and W.S. Pellini, "Correlations of Brittle-Fracture Service Failures with Laboratory Notch-Ductility Tests," Welding J. Res. Suppl. 37, 391-s (Sept. 1958).
16. R.W. Judy, Jr., C.N. Freed, and R.J. Goode, "A Characterization of the Fracture Resistance of Thick-Section Titanium Alloys," NRL Report 7427, July 5, 1972.

17. W.S. Pellini, "Criteria for Fracture Control Plans," NRL Report 7406, May 11, 1972.
18. W.S. Pellini, "Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels," NRL Report 6713, Apr. 1968.
19. M.T. Groves and J.F. Wallace, "Plane Strain Toughness of Cast Steels," Steel Founders' Society of America Research Report 81, Feb. 1975.
20. R.W. Judy, Jr. and R.J. Goode, "Ductile Fracture Equation for High-Strength Structural Metals," NRL Report 7557, Apr. 3, 1973.

GLOSSARY

a	length of the crack
b	ligament or net section of a specimen
B	thickness of the plate or specimen
C _v	Charpy-V test
DT	Dynamic Tear Test
DTE	Dynamic Tear Energy
DWT	Drop Weight Test
DWTT	Drop Weight Tear Test
FTE	Fracture Transition Elastic
FTP	Fracture Transition Plastic
J _c	critical value of the J-integral for characterization of elastic-plastic or plastic-fracture states
J _{Id}	dynamic-load opening mode J-integral value
K, K _I	stress-intensity factor; the subscript I denotes the opening mode of crack extension
K _{Ic}	slow-load (static), plane-strain fracture toughness
K _{Id}	dynamic-load, plane-strain fracture toughness
K _c	plane stress condition at crack tip for initiation; also, crack conditions in propagation as related to this fracture mode
L	plane-strain limit conditions
LEFM	Linear Elastic Fracture Mechanics
NDT	Nil Ductility transition temperature obtained by DWT or indexed by DT test
Q&T	quenched and tempered steel
RAD	Ratio Analysis Diagram
R _p	plastic resistance factor

Shelf	highest level of ductility attained at completion of constraint transition, due to temperature
w	specimen width
Y_c	yield criterion
σ	applied stress
σ_{yd}	yield strength for dynamic loading